2nd International Conference on Urban Disaster Reduction
November 27~29, 2007

A Comprehensive Areal Model of Earthquake-induced Landslides using Fuzzy Logic Systems

S. B. Miles [1*], ***D. K. Keefer*** [2]

[1] *Department of Environmental Studies, Western Washington University, Bellingham, WA, USA*

[2] *Western Region Earthquake Hazards Team, U.S. Geological Survey, Menlo Park, CA, USA*

Abstract

A new comprehensive areal model of earthquake-induced landslides (CAMEL), developed using fuzzy logic systems, is introduced here. CAMEL provides an integrated framework for modelling all types of earthquake-induced landslides using geographic information systems. CAMEL is designed to facilitate quantitative and qualitative representation of terrain conditions and knowledge about these conditions on the likely areal concentration of each landslide type. CAMEL is highly modifiable and adaptable; new knowledge can be easily added, while existing knowledge can be changed to better match local knowledge and conditions. CAMEL provides an open framework for incorporating other models with previously incompatible empirical and local knowledge. A brief overview of the model and example of its application is given here.

Keyword: *earthquake, landslide, GIS, fuzzy logic, hazard zonation*

[*] *Corresponding author address:* S. B. Miles, Department of Environmental Studies, Western Washington University, 516 High St. MS 9079, Bellingham, WA, USA, scott.miles@wwu.edu

1. Introduction

Presented here is a prototype GIS-based model of earthquake-induced landslide hazard developed using fuzzy logic systems. Landslides can be classified into three categories: (Category I) disrupted slides and falls, (Category II) coherent landslides, and (Category III) lateral spreads and flows [1]. Category I and II landslides occur in rock and soil, while Category III landslides occur only in soil. Considering landslide type in the context of disaster risk reduction is critical because of the strong relationship to the form (e.g., fatalities or structural damage) and severity of damage [1-3]. CAMEL currently evaluates the hazard from six aggregated types of earthquake-induced landslides: (Category I) disrupted soil slides, falls, and avalanches; disrupted rock slides and falls; rock avalanches; (Category II) soil slumps and block slides; rock slumps and block slides; and (Category III) rapid soil flows. Currently, CAMEL does not model lateral spread failures.

CAMEL was designed for transparency and adaptability to new or local knowledge, as well as to run with missing or incomplete data. CAMEL predicts areal landslide concentration (number of landslides per square kilometer) for each landslide type, as well as an uncertainty factor. The second section of this paper presents the conceptual framework and design of CAMEL. The implementation of CAMEL is described in the third section, with a brief example of its application. In the fourth section, the conclusion presents an outline of future work needed to further the development of CAMEL.

2. CAMEL Design

CAMEL was designed and implemented as a fuzzy logic system. Fuzzy logic systems are a subset of computing with words (CW) [4], which refers to a large body of methods and frameworks for numerically representing natural language for the purpose of characterizing uncertainty and propagating it using some calculus of logic. The foundation of CW is the concept of the fuzzy set [5]. Fuzzy sets can be thought of as expressing a degree of belonging ranging between zero (0) and one (1) to a particular category – zero indicating certain not-belonging and one indicating certain belonging. Fuzzy logic systems refer to a configuration of IF-THEN rules that relate the fuzzy sets of one or many input variables to fuzzy sets of one or more output variables. For a more detailed description of fuzzy logic systems refer to [6].

The first step in the development CAMEL or any fuzzy logic systems was knowledge elicitation. Knowledge elicitation for CAMEL from literature that describes analyses of past landslide-triggering earthquakes and extracting relevant numerical or correlative information [1,7-15]. Expert judgment was used to fill any gaps in knowledge from the literature. This knowledge can be revised or supplemented in the future using empirical data, existing models, or knowledge elicited from experts. For initial development of CAMEL, it is useful to be able to use empirical data and existing models to help evaluate the quality of the foundational sources of knowledge.

CAMEL is comprised of two modules—the possibility and hazard modules—each of which are made up of several fuzzy IF-THEN rule-blocks (Figure 1). The possibility module determines whether the occurrence of each respective landslide type is possible. Each rule block in the possibility module contains rules associated with a specific variable to collectively determine the degree to which, from zero to one, each landslide type is possible. The hazard module determines the relative hazard, expressed as areal landslide concentration, for each possible landslide type. The module treats each landslide type separately in two sub-modules: static susceptibility and seismic hazard. The seismic hazard sub-module was designed specifically for use with the ShakeMap product of the U.S. Geological Survey [16]. Importantly, as shown in Figure 1b, the possible range of concentration values is different for each landslide type.

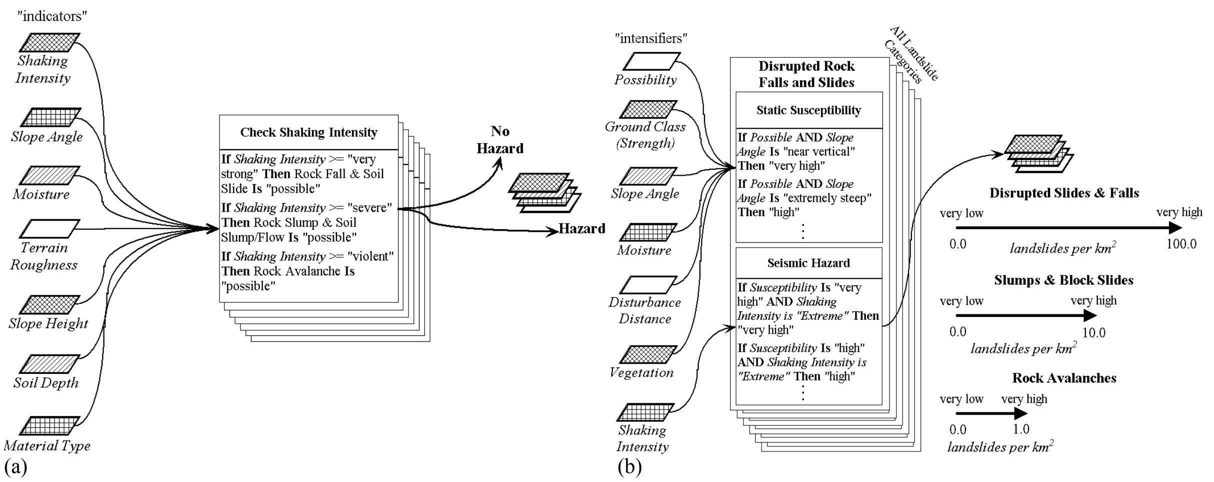

Figure 1. (a) Possibility module of CAMEL and (b) Hazard module of CAMEL, showing inputs, outputs (spatial frequencies of six landslide types), and rule organization.

3. CAMEL Implementation

CAMEL has been implemented in the fuzzy systems development environment FuzzyTech™ and integrated with ESRI's ArcGIS™ to permit regional analysis. In order to apply CAMEL for regional-scale modeling, several spatial data layers are required as inputs to the model, with other layers being optional (Figure 1). Required input data layers include slope gradient, terrain roughness (unsigned curvature), ground class (soil or rock strength index), degree of saturation, and ShakeMap intensity.

To illustrate outputs of CAMEL, it was applied to the 1:24,000 Laurel quadrangle, California (USA), which was the area of highest landslide concentration after the 1989 Loma Prieta earthquake [17]. A spatial data layer of shaking intensity during the M=6.9 event was obtained from the USGS ShakeMap site (http://earthquake.usgs.gov/eqcenter/shakemap/, 07/27/07). A 10-meter digital elevation model was used to calculate slope angle, slope height and terrain roughness. The ground class layer was based on a 1:100,000 geology map of the area [18]. Completely unsaturated conditions were assumed because of prevailing drought conditions at the time [17].

Output maps from CAMEL are shown in Figure 2. Two types of outputs are not shown: the possibility layer for each landslide slide type and the fuzziness (uncertainty) associated with each landslide concentration layer. Overlain on the maps (hollow circles) are the Category I landslides mapped after the Loma Prieta earthquake [17]. No distinction is made in the inventory between rock versus soil Category I landslides. Figure 2a presents the map of predicted concentrations of disrupted soil slides, falls, and avalanches with the Category I Loma Prieta landslides overlain. Figure 2b is a hazard map showing predicted disrupted rock slide and fall concentrations for the Loma Prieta earthquake scenario described above. The predicted concentrations of rock avalanches for the Loma Prieta earthquake are shown in Figure 2c. The Loma Prieta earthquake did not trigger any landslides classified as rock avalanches [17]. No maps are shown for Category II and III landslides because CAMEL predicted that, under the assumed dry conditions, these landslide types are impossible. There were 94 Category II landslides in the Laurel quadrangle triggered by the Loma Prieta earthquake and no Category III landslides [17].

4. Conclusion

Based on visual comparison, CAMEL predictions are generally consistent with the Loma Prieta landslide inventory, at least for Category I landslides. CAMEL appears to perform best with respect to disrupted soil slides, falls, and avalanches, while over-predicting the areal concentration of rock avalanches and disrupted rock slides and falls. Based on the detail of information available (or that can be inferred) regarding the Loma Prieta landslides, CAMEL seems to appropriately distinguish between the different landslide types.

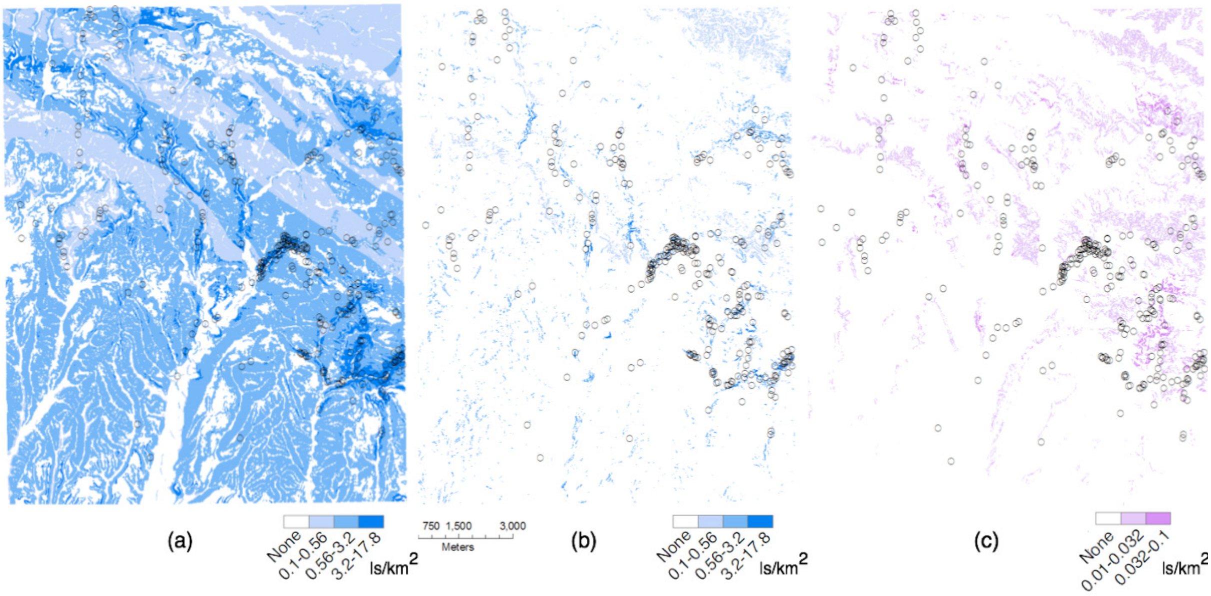

Figure 2. CAMEL output maps for the Laurel quadrangle, California (USA), modeling the 1989 Loma Prieta earthquake: (a) Disrupted soil slides, falls, and avalanches; (b) disrupted rock slides and falls; and (c) rock avalanches. Category I landslide mapped after the Loma Prieta earthquake [17] shown as hollow black circles.

Clearly, more work is required to develop and evaluate CAMEL. CAMEL should be compared against (and modified to incorporate knowledge from) landslide inventories from other past earthquakes, including the Northridge, California and Chi-Chi, Taiwan earthquakes. Beyond further evaluation, there are several obvious modifications that will improve CAMEL. It may be desirable to treat each actual landslide type separately. Lateral spread failures should be built in as part of CAMEL. A significant improvement to CAMEL would be to represent the velocity and size of potential landslides. CAMEL is suited for planning related to disaster risk reduction because it is highly modifiable and adaptable; new knowledge can be easily added, while existing knowledge can be changed to better match local knowledge and conditions. As such, CAMEL should not be viewed as a complete alternative to other models. In fact, the outputs or knowledge of other models can be integrated into CAMEL. For example, Newmark displacements could be integrated as a possible input for predicting concentrations of some landslide types.

5. References

[1] Keefer D.K., Landslides caused by earthquakes, Geological Society of America Bulletin, Vol. 95, No. 4, (1984), pp. 406-421.

[2] Cruden D., Varnes D., Landslide types and processes, in: A. Turner, R. Schuster (Eds.), Landslides: Investigations and mitigation, National Academy Press, Washington, DC, 1996, pp. 36--75.

[3] Schuster R., Highland L., Socioeconomic and environmental impacts of landslides, U.S. Geological Survey Open-File Report 2001-276, 2001.

[4] Zadeh L.A., Fuzzy logic equals computing with words, IEEE Transactions on Fuzzy Systems, Vol. 4, No. 2, (1996), pp. 103-111.

[5] Zadeh L.A., Fuzzy Sets, Information and Control, Vol. 8, No. 3, (1965), pp. 338-353.

[6] Miles S.B., Keefer D.K., Comprehensive areal model of earthquake-induced landslides: Technical specification and user guide, U.S. Geological Survey Open-File Report 2007-1072, 2007, p. 69.

[7] Bommer J.J., Rodriguez C.E., Earthquake-induced landslides in Central America, Engineering Geology, Vol. 63, No. 3-4, (2002), pp. 189-220.

[8] Keefer D.K., Earthquake-induced landslides and their effects on alluvial fans, Journal of Sedimentary Research, Vol. 69, No. 1, (1999), pp. 84-104.

[9] Keefer D.K., Statistical analysis of an earthquake-induced landslide distribution - the 1989 Loma Prieta, California event, Engineering Geology, Vol. 58, No. 3-4, (2000), pp. 231-249.

[10] Keefer D.K., Investigating landslides caused by earthquakes - A historical review, Surveys in Geophysics, Vol. 23, No. 6, (2002), pp. 473-510.

[11] Liao C., Lee C., Liao H., Statistical analysis of factors affecting landslides triggered by the 1999 Chi-Chi earthquake, Taiwan, Transactions of the American Geophysical Union Fall Meeting, Vol. 83, No. 47, (2002).

[12] Parise M., Jibson R.W., A seismic landslide susceptibility rating of geologic units based on analysis of characteristics of landslides triggered by the 17 January, 1994 Northridge, California earthquake, Engineering Geology, Vol. 58, No. 3-4, (2000), pp. 251-270.

[13] Rodriguez C.E., Bommer J.J., Chandler R.J., Earthquake-induced landslides: 1980-1997, Soil Dynamics and Earthquake Engineering, Vol. 18, No. 5, (1999), pp. 325-346.

[14] Keefer D.K., The susceptibility of rock slopes to earthquake-induced failure, Association of Engineering Geologists Bulletin, Vol. 30, No. 3, (1993), pp. 406-421.

[15] Hancox G., Perrin N., Dellow G., Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in New Zealand, Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 35, No. 2, (2002), pp. 59-95.

[16] Wald D., Heaton T., Kanamori H., Scrivner C., Worden C., TriNet ShakeMaps: Rapid generation of instrumental ground motion and intensity maps for earthquakes in Southern California, Earthquake Spectra, Vol. 15, No. 3, (1999), pp. 537-556.

[17] Keefer D.K. (Ed.), The Loma Prieta, Californa earthquake of October 17, 1989 -- Landslides, U.S. Geological Survey Professional Paper 1551-C, 1998.

[18] McLaughlin R., Clark J., Brabb E., Helley E., Colón C., Geologic maps and structure sections of the Southwestern Santa Clara Valley and Southern Santa Cruz Mountains, Santa Clara and Santa Cruz Counties, California, U.S. Geological Survey Miscellaneous Field Studies Map MF-2373, 2001.